Genetic Algorithm and Backstepping Controller for Photovoltaic System under Partial Shading Effect

Cheikhne Cheikh Ahmed*‡, Mohamed Cherkaoui*, Mohcine Mokhlis*, and Mouad Bahij*

* Department of Electrical Engineering, Mohammadia School of Engineers, Mohammed V University in Rabat, Ibn Sina Street P.B 765, Rabat

(Cheikhna03@yahoo.fr, cherkaoui@emi.ac.ma, mohcine1mo@gmail.com, mouad.t18@gmail.com)

‡ Corresponding Author; Cheikhne Cheikh Ahmed, Tel: +212 624 178 475,

Cheikhna03@yahoo.fr

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Abstract- Since the weather conditions are variable and unpredictable, and the PV power depends heavily to these conditions, different MPPT and GMPPT techniques are proposed and improved to make the photovoltaic power works at its maximum of power. In this context, this paper proposes a novel global maximum power point tracking technique based on the genetic algorithm combined with the Backstepping controller. The genetic algorithm serves for looking for the reference voltage corresponding to the global maximum power point, while the robust Backstepping controller is designed to follow this reference by acting on the duty cycle of the SEPIC converter. The performances of the proposed technique are tested and validated by comparing the proposed technique with the P&O-SMC, P&O-BSC, InC-SMC and InC-SMC MPPT techniques, and the GMPPT technique based PSO-SMC. The results have seen that the proposed technique can successfully track the global maximum while the MPPT techniques falling on the local maximum in some cases. In addition, the results show the performances criteria, of the proposed technique, which are better than the PSO-BSC technique tracking performances under the partial shading effect.

Keywords Backstepping controller, Genetic algorithm, GMPPT, Partial Shading Effect, Photovoltaic panel.

Nomenclature

GMPP	: Global Maximum Power Point
LMPP	: Local Maximum Power Point
GMPPT	: Global Maximum Power Point Tracking
MPPT	: Maximum Power Point Tracking
MPP	: Maximum Power Point
PSO	: Particle Swarm Optimization
P-V	: Power-Voltage curve
I_{rr_i}	: Irradiation in each PV module $i = \{1,2,3\}$
N_s	: Number of series modules
N_p	: Number of parallel modules
N_{cell}	: Number of series cells
q	: The electron charge
I_s	: Saturation current
I_{ph0}	: Photocurrent measured under STC
K_i	: Temperature coefficient of the short circuit-current
E_G	: Band-gap energy
A	: Ideality factor
PV	: PhotoVoltaic
GA	: Genetic Algorithm
P&O	: Perturb & Observe
InC	: Incremental Conductance
BSC	: Backstepping Controller
SMC	: Sliding Mode Controller
K	: Boltzmann Constant
V_{OC}	: Open-Circuit Voltage

I_{scr} : Short-Circuit Current

I_{pv} : Photovoltaic Current

V_{pv} : Photovoltaic Voltage

I_{ph} : Photocurrent

R_p : Parallel resistor

R_s : Series resistor

STC : STandard Conditions

T : Ambient temperature

1. Introduction

Currently, the majority of electric power generation is based on non-renewable resources such as the natural gas, coal and petroleum, which present the major part of the world's electricity production. However, these resources risk depleting in the next few years. Moreover, these resources cause a dangerous environmental pollution on nature, as well as production of a large amount of CO2 into the atmosphere, which seriously affects the environmental nature. That obliged the governments to review their energy policies and start introducing renewable energy resources into power generation systems by using new clean and renewable resources [1]-[2].

There are three most important renewable sources divided between the hydroelectric power, the wind power, and the solar energy. In fact, the solar energy, or precisely the photovoltaic energy, is more requested thanks to its availability and ability to be installed close to the consumer, and ease of installation [3]. In addition, this energy does not require a lot of repetitive maintenance, which makes it more efficient and profitable than the other renewable energy.

The elementary photovoltaic cell constitutes a generator of very low power compared to the needs of most domestic or industrial applications. An elementary cell of a few tens of square centimeters delivers, at most, a few watts at a voltage lower than one volt (PN junction voltage). To produce more power, several cells must be combined to create a module or a photovoltaic panel. Connecting the cells in series makes it easy to increase the voltage of the assembly, while paralleling makes it possible to increase the current. Series / parallel (or mixed) wiring is therefore used to obtain a PV generator with the desired characteristics.

During the operation of the photovoltaic resources, the photovoltaic panels (PV) are exposed to the variable weather conditions (the temperature and the irradiation). In fact, the meteorological conditions change randomly during the day, which makes the operation power point position also changes. So, to make the photovoltaic system works at its maximum power, the maximum power point tracking techniques (MPPT) are extremely proposed for this purpose [4]-[5].

Until today, several MPPT methods are proposed. The perturb and observe (P&O) method [6]-[7] is the most used algorithm because of its simplicity and ease of implementation. This algorithm disturbs the photovoltaic voltage, as well as the duty cycle of the PV system, and then observes the derivative of power as a function of voltage in order to define the right direction of the Maximum Power Point (MPP). The incremental conductance (InC) [8]-[9] is the improved version of the P&O algorithm that serves for the rapid changes of meteorological conditions. These two algorithms (P&O and InC) have a major drawback, which is the compromise rapidity-precision that refers to the step size of changing the duty cycle.

Some MPPT techniques, based on the artificial intelligence such as the Artificial Neural Network (ANN) [10]-[11] and the Fuzzy logic controller (FLC) [12]-[13], have been proposed thanks to their rapidity for tracking the MPP. The ANN is more advantageous thanks to its rapid prediction the optimal voltage that corresponds to the MPP basing on a database. These MPPT techniques, despite their good tracking performances, remain unable to track the Global Maximum Power Point (GMPP) when the partial shading takes place. Therefore, they causes high losses of power under the partial shading effect.

In fact, under the partial shading conditions, the Power-Voltage curve (P-V) presents several maximum power points divided between local and global maximums. The MPPT techniques cannot distinguish the global maximum, which motivate researchers to look for new techniques able to solve this issue. Effectively, several Global Maximum Power Point Tracking Techniques (GMPPT) have been proposed in the literature, among which there are the cuckoo search [14], the Particle Swarm Optimization (PSO) [15]-[16], the Genetic Algorithm (GA) [17] and Ant Colony Optimization (ACO) [18]. These methods are able to observe the whole P-V curve, mark all the power peaks and define the highest peak as the Global Maximum Power Point (GMPP).

Based on the above analysis, this paper proposes a new hybrid technique for controlling the PV system and extract the global maximum power point, this technique consists of the genetic algorithm and the robust Backstepping Controller (BSC). The genetic algorithm serves for generating the optimal reference voltage that corresponds to the GMPP, while the BSC is designed to follow the reference voltage by adjusting the duty cycle of the DC-DC converter.

This paper is organized as follows. The second section covers the modelisation of the PV module as well as the SEPIC converter. The third section presents the proposed method. While the forth and the last sections present the simulation results and conclusion, respectively.

2. Proposed Photovoltaic System

This section presents modeling of the proposed photovoltaic system. The studied PV system, see Fig. 1, consists of three essential components, which are a photovoltaic panel composed of three modules of $55W$, connected in series, and feed a resistive load of 120Ω through a DC-DC converter (Type: SEPIC).

2.1. Modelling of a Photovoltaic Module

The modeling of the photovoltaic module is based on the modeling principle of a single diode PV cell that consists of two resistors R_s and R_p, a diode and a current source. The mathematical modeling of the PV module is given by the following expression as described in [19]:

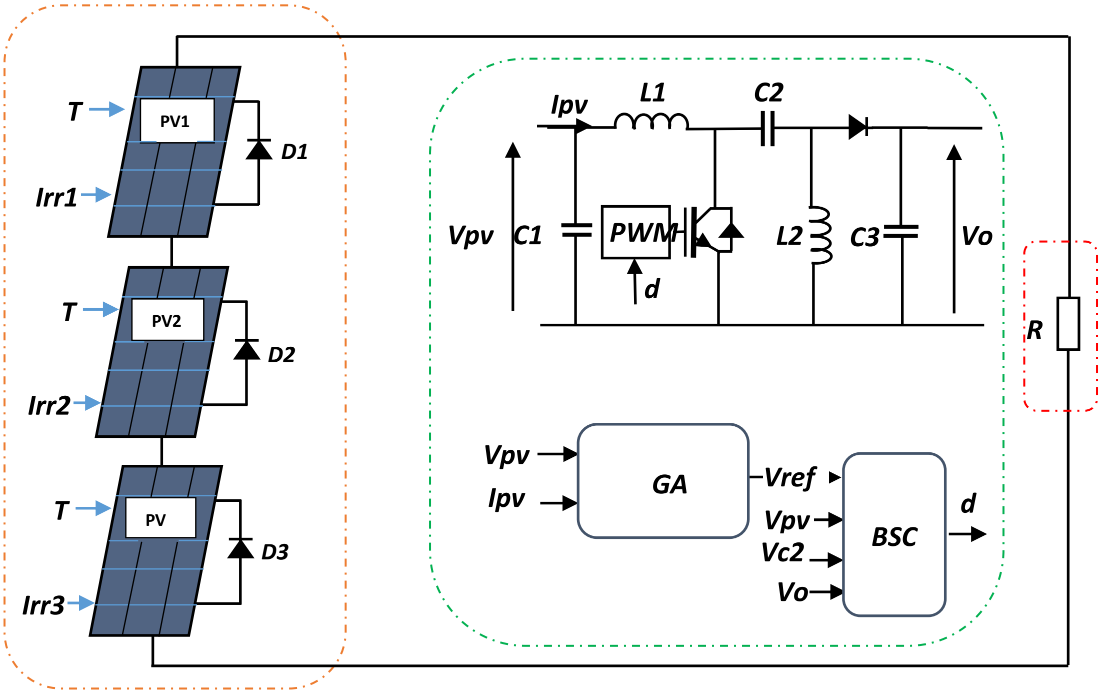


Fig. 1. Studied PV system.

$$I_{pv} = N_p I_{ph} - N_p I_s \left[e^{\left(\frac{qV_{pv}+I_{pv}R_s}{N_s N_{cell} AKT}\right)} - 1 \right] + \frac{V_{pv} + I_{pv}R_s}{R_p} \quad (1)$$

Where;

I_{ph} is the photocurrent, it is given by the following formula [19]:

$$I_{ph} = [I_{ph0} + (K_i(T - T_{stc}))] \frac{I_{rr_i}}{I_{rr\,stc}} \quad (2)$$

With I_{ph0} is the Photocurrent measured under STC (Irradiation of $I_{rr\,stc} = 1000W/m^2$ and temperature of $T_{stc} = 25°C$).

The saturation current I_s can be expressed as follows:

$$I_s = I_{s0} (\frac{T}{T_{stc}})^3 e^{(\frac{qE_G}{KA}(\frac{1}{T_{stc}} - \frac{1}{T}))} \quad (3)$$

With E_G is the band-gap energy. $E_G \approx 1.12Ev$ for polycrystalling silicon solar cells [19].

The reverse saturation current I_{s0} measured at STC is:

$$I_{s0} = \frac{I_{scr}}{e^{(\frac{qV_{oc}}{KN_s AT})} - 1} \quad (4)$$

Based on Eq. (1), the photovoltaic module's power P_{pv} can be expressed as follows:

$$P_{pv} = V_{pv} N_p I_{ph} - N_p V_{pv} I_s \left[e^{\left(\frac{qV_{pv}+I_{pv}R_s}{N_s N_{cell} AKT}\right)} - 1 \right] + V_{pv} \frac{V_{pv} + I_{pv}R_s}{R_p} \quad (5)$$

2.2. DC-DC converter

The DC-DC converter (Type: SEPIC) is used in this study as an adaptation stage that can control the photovoltaic power under partial shading effect. Effectively, the DC-DC converter is necessary for controlling the photovoltaic voltage to pursue its optimum, thus, to allow the photovoltaic power to track the global maximal power point. In fact, the proposed technique controls continuously the duty cycle of this converter to achieve the expected purpose. Referring to [20], the average model of the SEPIC converter can be described by the following state equations:

$$\begin{cases} \dot{V}_{pv} = \frac{1}{C_1} I_{pv} - \frac{1}{C_1} I_{L1} \\ \dot{I}_{L1} = \frac{1}{L_1} V_{pv} - \frac{1}{L_1}(1-d)(V_{C2}+V_o) \\ \dot{V}_{C2} = \frac{1}{C_2}(1-d) I_{L1} + d\frac{1}{C_2} I_{L2} \\ \dot{I}_{L2} = d\frac{1}{L_2} V_{C2} - (1-d)\frac{1}{L_2} V_o \\ \dot{V}_o = \frac{1}{C_3}(I_{L1}+I_{L2})(1-d) - \frac{1}{C_3 R} V_o \end{cases} \tag{6}$$

The following sections present details about the existing and the proposed GA-BSC techniques.

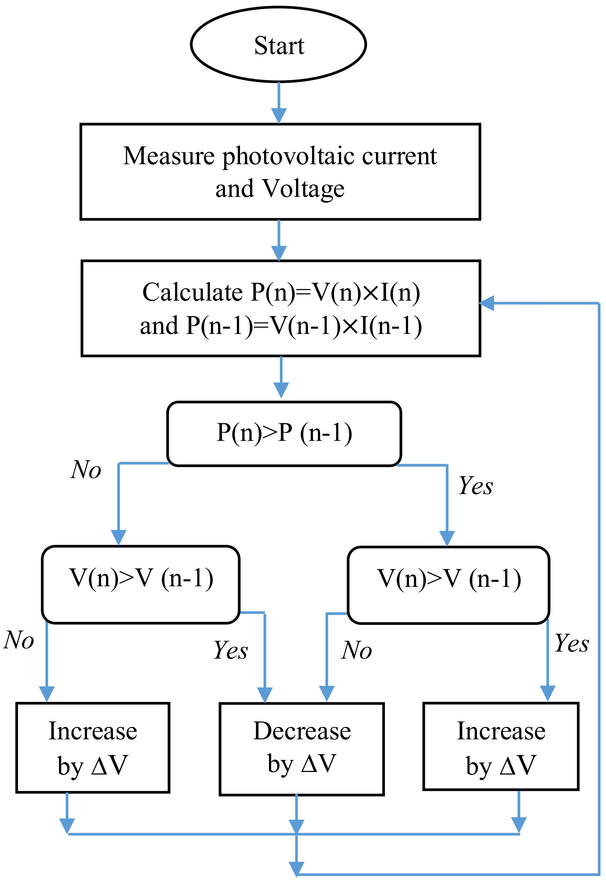


Fig. 2. P&O algorithm.

3. Conventional MPPT and Proposed GA-BSC Based GMPPT Techniques

The MPPT techniques are mainly dedicated to the PV modules under uniform insolation. Indeed, thanks to its ability to pursue the maximum power point, researchers proposed different methods able to locate and track the MPP. There are the Perturb and observe technique, the incremental conductance technique and the hybrid techniques like the P&O or InC combined with the Backstepping controller [19]-[20]. In addition, there are techniques based GMPPT like the PSO algorithm combined with the Sliding Mode Controller [16]. These techniques are detailed briefly in the next subsections.

3.1. P&O MPPT

The P&O algorithm, see Fig. 2, is one of the iterative MPPT methods widely used in the literatures. This conventional MPPT technique is based on the perturbation of the photovoltaic voltage and observation of the sign of the power variation as a function of voltage variation. In fact, if $\left(P(n)-P(n-1)\right)/\left(V(n)-V(n-1)\right)>0$, this technique disturbs the voltage by $+\Delta V$, with ΔV is the variation step of voltage. While, if $\left(P(n)-P(n-1)\right)/\left(V(n)-V(n-1)\right)<0$, the P&O algorithm disturbs the voltage by $-\Delta V$. In fact, because of the variation step's size, this algorithm poses compromise between rapidity and accuracy [3].

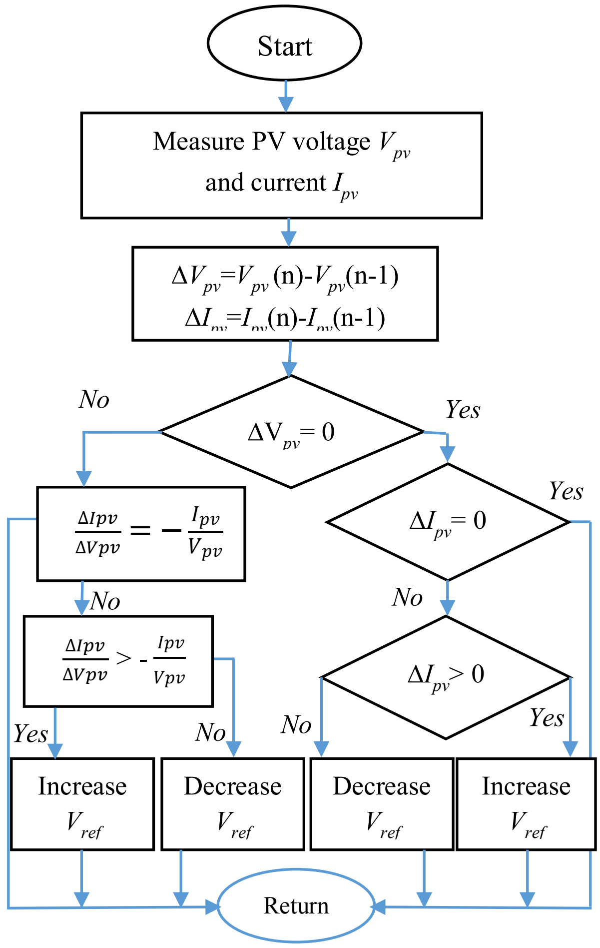


Fig. 3. InC algorithm.

3.2. InC MPPT

The incremental conductance is a conventional iterative algorithm, based MPPT technique, used to eliminate gaps encountered in the P&O algorithm. The InC algorithm technique is more performant than the P&O algorithm under rapid changes of weather conditions. Indeed, in contrary to the P&O algorithm, the InC algorithm perturbs the voltage accordingly to the sign of $\Delta V/\Delta I$ that presents the variation of voltage as a function of current variation as described in Fig.3.

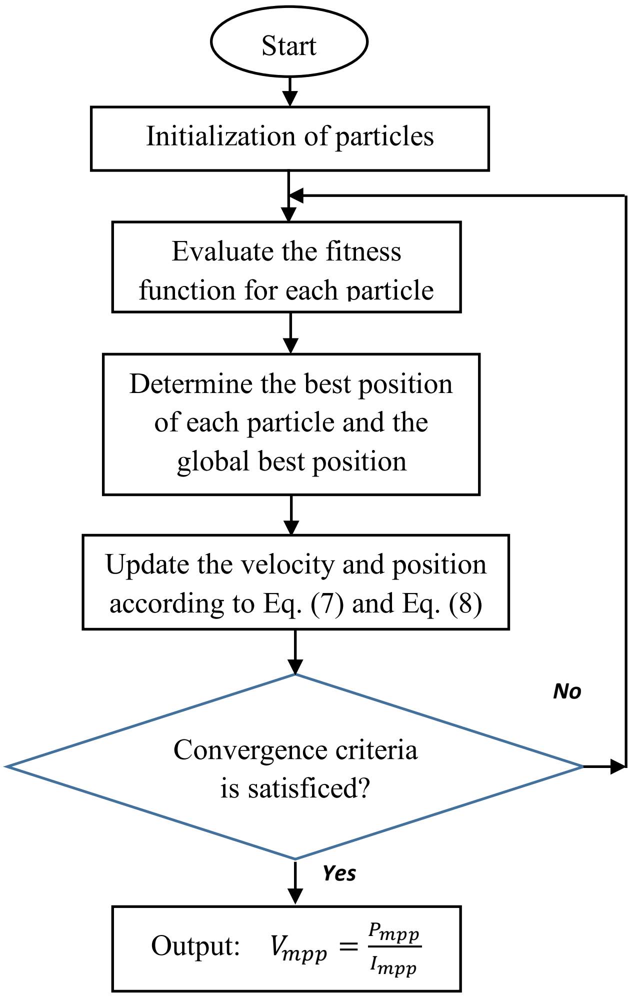


Fig. 4. PSO Flowchart.

3.3. PSO GMPPT

The Particle Swarm Optimization (PSO) algorithm was proposed by Kennedy and Eberhart in 1995 [16]. This algorithm based GMPPT technique can skip the local maximum each time a new global maximum is located, which makes this algorithm more efficient than the most known MPPT techniques under the partial shading effect. Indeed, this algorithm is based on the birth flocking's behavior. The PSO algorithm uses particles representing the potential solutions to a problem. Each particle flies into a research space with a speed that can be adjusted based on the current flight experiences. The speed of the particle v_i at $(t + 1)^{th}$ iteration and the projected position of the i^{th} particle of the swarm x_i, are defined by the following equations:

$$v_i^{k+1} = wv_i^k + c_1r_1\left(p_{i_{best}} - x_i^k\right) + c_1r_1\left(g_{best} - x_i^k\right) \quad (7)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (8)$$

With;

w	:	The weight of inertia.
c_1, c_2	:	The acceleration coefficients.
r_1, r_2	:	The random numbers limited between *0* and *1*.

4. Proposed GA-BSC Based GMPPT Technique

4.1. GA GMPPT

The genetic algorithm is inspired from biology, it exploits exactly the idea of reproduction (Darwin) so that genes passed from one generation to another. The GA can deal with the wide variety of problems, such as surveillance, and it is inspired by the mechanism of natural selection where the strongest individuals in the population have a higher probability of surviving and producing children in a competitive environment. With genetic evolution technique, the optimal solution can be defined and represented by the winning set of the genetic operation.

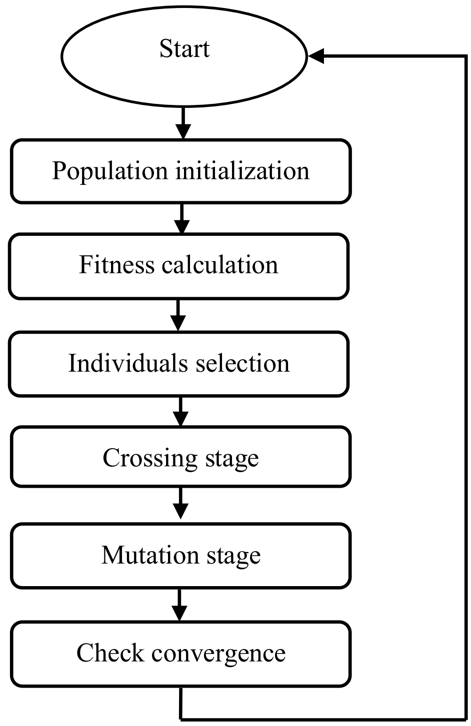


Fig. 5. Genetic algorithm flowchart.

The process of the genetic algorithm (GA) is based on four steps described in the following lines:

- Identify the objective function in order to quantify the suitability of each candidate solution. In this paper, this function searches for the maximum global power point when partial shading occurs.
- Initialize and transmit the population randomly (see fig. 5.). The population size consists of six individuals that represent voltage values to be transmit successively to the Backstepping controller.
- Assess the suitability of each individual.
- Create a new population based on the natural genetic process. Once the stopping criteria are met or the

number of generations is reached, the algorithm is stopped.

In this work, the objective function serves to find the global maximum power point, and define the PV modules' optimal voltage that is limited between $0V$ and V_{oc}.

At the start of the search process, the GA launches an initial population vector chosen to cover the interval $[0V,\ V_{oc}]$ that presents the search space for the optimum reference voltage that corresponds to the desired GMPP. The initial population proposed is a vector composed of six individuals $[V_1, V_2, V_3, V_4, V_5$ and $V_6]$. These individuals are transmitted one after other in the form of reference voltages to the DC-DC converter. Once the optimum reference voltage is set, the global maximum power is reached, this power is measured and stored, and the next individual is called to take a turn etc. After that, all the individuals of the generation have been tested, the selection is carried out by elitism. Crossbreeding involves combining two individual parents to produce a child. This step is based on Eq. (9).

$$v_i(n) = rand(1)v_i(n-1) + (1 - rand(1))v_j(n-1) \tag{9}$$

The mutation of individuals occurs with a very low probability. In this step, the algorithm randomly makes a change in individuals by using Eq. (10).

$$v_i(n) = v_{min} + rand(1)(v_{max} - v_{min}) \tag{10}$$

Where V_{max} and V_{min} are respectively the maximum and minimum voltages in the search space. To avoid or minimize the fluctuations usually caused by the mutation, the conditions (11) and (12) are used to stop the search process in order to select the best solution among all the generations as an optimal reference voltage. The algorithm has been changed to reset the search process whenever a change in temperature or solar irradiation is detected. Indeed, the genetic algorithm (GA) is reset when the following conditions are true:

$$|v(n+1) - v(n)| < \Delta v \tag{11}$$

$$\left|\frac{p_{pv}(n+1) - p_{pv}(n)}{p_{pv}(n)}\right| > \Delta p_{pv} \tag{12}$$

4.2. Backstepping Controller

Step 1: Defining the first tracking error:

$$\epsilon_1 = y - y_{ref} = V_{pv} - V_{ref} \tag{13}$$

Knowing that the time derivative of ϵ_1 is:

$$\dot{\epsilon}_1 = \dot{V}_{pv} - \dot{V}_{ref} \tag{14}$$

Consequently, replacing $\dot{V}_{pv}$ by its expression shown in Equ. (6), Equ. (14) would be as follows:

$$\dot{\epsilon}_1 = \frac{I_{pv} - i_{L1}}{c_{pv}} - \dot{V}_{ref} \tag{15}$$

Considering the following Lyapunov function:

$$V_1(\epsilon_1) = \frac{1}{2}{\epsilon_1}^2 \tag{16}$$

The derivative of $V_1(\epsilon_1)$ gives:

$$\dot{V}_1(\epsilon_1) = \epsilon_1\dot{\epsilon}_1 = \epsilon_1\left(\frac{I_{pv} - I_{L1}}{C_{pv}} - \dot{V}_{ref}\right) \tag{17}$$

To ensure the Lyapunov stability, the time derivative of the Lyapunov function $V_1(\epsilon_1)$ has to be negative. Effectively, that can be reached when the following condition is true:

$$\frac{I_{pv}\alpha_1}{C_{pv}} - \dot{V}_{ref} = -K_1\epsilon_1 < 0 \tag{18}$$

With K_1 is a positive parameter ($K_1 > 0$) that can be chosen in order to reach desired performances' criteria.

Considering the virtual control $\alpha_1 = (I_{L1})_d$ that allows the stabilization of ϵ_1. Where $(I_{L1})_d$ is the desired value of the first inductor's current. Thus, based on Equ. (18), the virtual control α_1 can be expressed as follows:

$$\alpha_1 = -C_{pv}\dot{V}_{ref} + I_{pv} + C_{pv}K_1\alpha_1 \tag{19}$$

Step2 :

Now, let us define a new tracking error:

$$\epsilon_2 = I_{L1} - \alpha_1 \tag{20}$$

Using Equ. (6) and Equ. (20), the time derivative of ϵ_2 can be expressed as follows:

$$\dot{\epsilon}_2 = \frac{1}{L_1}V_{pv} - \frac{1}{L_1}(1-d)(V_{C2} + V_o) - \dot{\alpha}_1 \tag{21}$$

Where;

$$\dot{\alpha}_1 = -C_{pv}\ddot{V}_{ref} + \dot{I}_{pv} + C_{pv}K_1\dot{\alpha}_1 \tag{22}$$

Considering the second Lyapunov function $V_2(\epsilon_1, \epsilon_2)$:

$$V_2(\epsilon_1, \epsilon_2) = V_1(\epsilon_1) + \frac{1}{2}{\epsilon_2}^2 \tag{23}$$

Its time derivative can be expressed as follows:

$$\dot{V}_2(\epsilon_1, \epsilon_2) = \dot{V}_1(\epsilon_1) + \epsilon_2\dot{\epsilon}_2 \tag{24}$$

Considering the following new expression of $\dot{V}_1(\epsilon_1)$:

$$\dot{V}_1(\epsilon_1) = -K_1{\epsilon_1}^2 - \frac{\epsilon_1\epsilon_2}{C_{pv}} \tag{25}$$

Consequently;

$$\dot{V}_2(\epsilon_1, \epsilon_2) = -K_1{\epsilon_1}^2 - \frac{\epsilon_1\epsilon_2}{C_{pv}} + \epsilon_2\dot{\epsilon}_2 \tag{26}$$

To achieve the Lyapunov stability, $\dot{V}_2(\epsilon_1, \epsilon_2)$ should be negative, thus, the following condition has to be satisfied:

$$-\frac{\epsilon_1}{C_{pv}} + \dot{\epsilon}_2 = -K_2\epsilon_2 < 0 \tag{27}$$

With K_2 is appositicve onstant ($K_2 > 0$) that presents a regulation parameter.

Therefore, based on Equ. (27) and replacing $\dot{\epsilon}_2$ by its expression given in [21], the real control is concluded:

$$d = \left[L_1\left(-K_2\epsilon_2 + \frac{\epsilon_1}{C_{pv}} + \dot{\alpha}_1\right) - V_{pv}\right]\frac{1}{V_{C1}+V_{out}} + 1 \qquad (28)$$

Thus;

$$\dot{V}_2(\epsilon_1, \epsilon_2) = -K_1{\epsilon_1}^2 - K_2{\epsilon_2}^2 < 0 \qquad (29)$$

Which ensures converging ($\epsilon = \epsilon_1, \epsilon_2$) asymptotically to 0. Thus, convergence of y to y_{ref}.

5. Simulation Results

This section mainly focuses on discussing results obtained by the proposed technique under uniform and non-uniform meteorological conditions. Then, it presents drawbacks of the MPPT techniques under non-uniform meteorological conditions, as well as advantages of the proposed technique based GMPPT under different cases of the meteorological conditions. The proposed technique is validated under Matlab/SIMULINK environment.

The proposed PV system, see Fig. 1, is composed of three photovoltaic modules (Reference: Shell SM55 [16]) connected in series and feed a resistive load of 120Ω through an adaptation stage (a DC/DC converter type: SEPIC). Knowing that the maximal power that can produces each PV module is approximately $55W$, thus, the studied photovoltaic source can produce a maximal power of $165W$ under the standards meteorological conditions (Irradiation of $1000\,{}^{W}/_{m^2}$ and temperature of $25°C$).

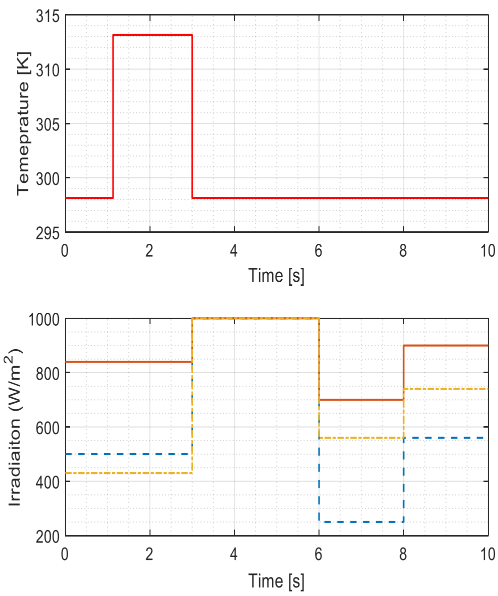


Fig. 6. Studied meteorological conditions.

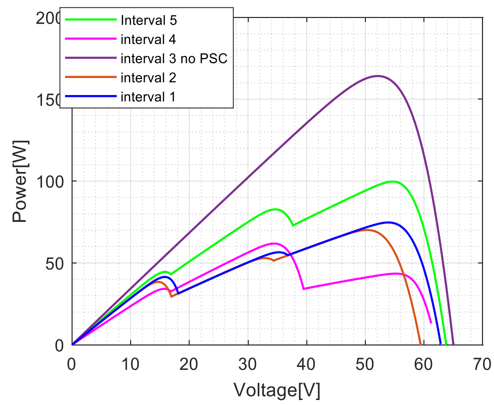


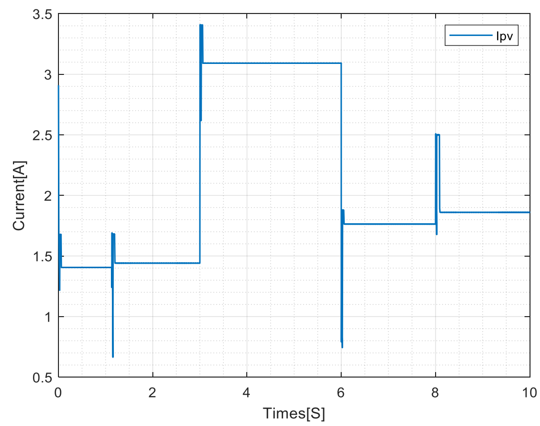
Fig. 7. Power-Voltage Caracteristics.

Parameters of the SEPIC converter:

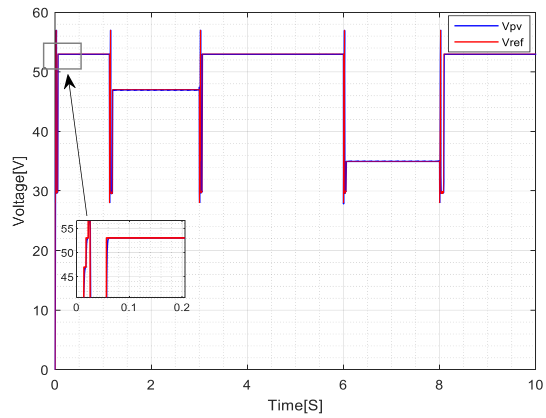
$C_1 = 440\mu F$, $C_2 = 440\mu F$, $L_1 = 0.35mH$, $L_2 = 0.35mH$, $C_3 = 470\mu F$.

Backstepping controller parameters:

$K_1 = 10^6$, $K_2 = 1.5 \cdot 10^3$.



(a)



(b)

Fig. 8. Photovoltaic current and voltage using the proposed GA-BSC technique.

Considering the PV source is subjected to the meteorological conditions illustrated in Fig. 6. So, from this figure, it can be noted that the three PV modules are considered subjected to the uniform ambient conditions during the time interval [3s, 6s]. especially, for an irradiation of $1000w/m^2$ and a temperature of $25°C$ that present the standards conditions that allow to the PV modules to operate at their maximum of power. While, during the other time intervals, the PV modules are considered subjected to the non-uniform ambient conditions (partial shading effect).

Figure 7 shows the P-V caracteristics obtained for the five cases of meteorological conditions illustrated in Fig. 6.

From Fig. 9 it can be seen that the MPPT and GMPPT techniques succeed to follow the MPP, in addition, the GMPPT techniques, especially the proposed one present high tracking performances (accuracy and rapidity). On the one hand, when the partial shading occurs, the MPPT techniques (InC-SMC, P&O-SMC, P&O-BSC, InC-BSC) causes the considerable losses of power because they are not devoted to tracking the global maximum power point. Also, as illustrated in Fig. 9., these MPPT techniques make the PV power oscillate around the GMPP. In fact, these algorithms present compromise rapidity-accuracy because of the fixed increment step of voltage. On the other hand, it can be seen that the GA is faster than the PSO algorithm which means that the GA algorithm is more performant and can be used instead of the PSO algorithm. In fact, the PSO is designed using four initial particles while the GA is designed with population of six initial individuals which make the GA faster and accurate than the PSO.

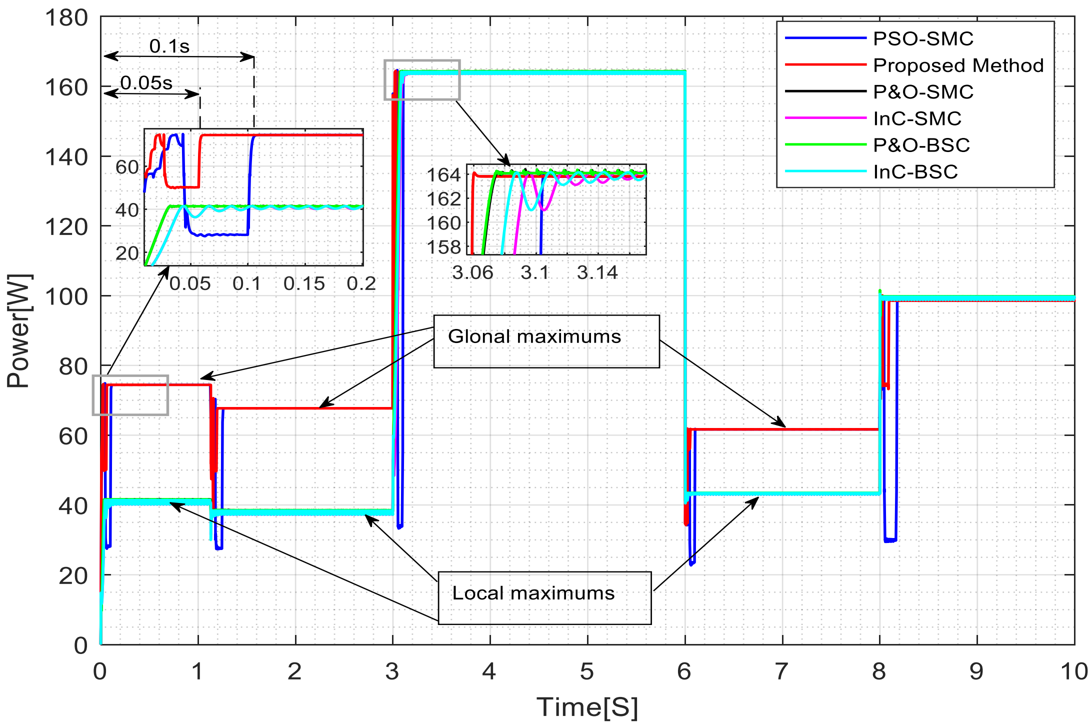


Fig. 9. Comparison of MPPT and GMPPT techniques.

In addition, using the hybrid GMPPT algorithm, which consists of two powerful-cascaded controllers (GA and BSC or PSO and BSC), can increase tracking performances of the overall PV system.

Figure 8(a) and Fig. 8(b) illustrate the photovoltaic current and voltage produced using the proposed GA-BSC technique. So, as can be seen in Fig. 8(b), the photovoltaic voltage tracks quickly and accuracy the reference voltage thanks to the Backstepping technique that is devoted to the control of the proposed nonlinear system (SPEIC and PV source).

6. Conclusion

This paper proposes new GMPPT technique based on the genetic algorithm and the Backstepping controller. On the one hand, based on the simulation results, which are generated by MATLAB-Simulink software, it has demonstrated that the MPPT techniques have a major drawback and cause a power loses when the partial shading takes place. Nevertheless, under uniform meteorological conditions, these techniques can track the maximal power point. On the other hand, the proposed technique, which combines the GA algorithm that allows tracking the global maximal power point and the Backstepping controller that is able to control the nonlinear systems, has demonstrated its tracking performances' criteria for presenting high speed of convergence, negligible oscillations around the GMPP and aroung the MPP, and especially its capability of detecting the partial shading effect. Thus, after combining two powerfull controllers, one coming from the optimization algorithms and other coming from the nonlinear controllers and enhancing the GA performances by using population of six individuals, this led to a novel hybrid controller that made the performant efficeint PV system. Consuquently, the proposed technique can be used in the future works instead of the existing techniques (especially techniques discussed in this paper) for controlling PV systems under uniform meteorological conditions or partial shading effect.

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